XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Effect of Moisture History on ASR Expansion and Microstructural Properties

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Abstract. *Alkali Silica reaction has been a great menace to the durability of concrete infrastructure since its discovery. The mechanism is caused by the reaction between poorly crystallized silica and alkalis in the presence of sufficient amount of water. Just as water plays a critical role in several durability challenges in concrete, the limitation of moisture has been prominently used as a technique for the maintenance of ASR affected structures. The variation in moisture condition to which structures are exposed could lead to alternate wet and dry regimes. Drying aids the mitigation of the reaction, however, the cyclic phenomenon can modify the kinetics of the reaction and exercebate inner damage. This paper focuses on the development of the reaction over an alternate wetting and drying cycle involving aggregates of different levels of reactivity. The influence of the moisture history on the microscopic features were appraised using the damage rating index. The kinetics of the reaction and ASR induced deterioration in specimens undergoing cycles of wet and dry conditions differ when compared to those stored at constant moisture. Furthermore, ASR induced expansion and petrographic features are influenced by the difference in the reactivity level of aggregates.*

Keywords: *Alkali silica reaction (ASR); Moisture; Damage rating index (DRI); Wetting and Drying; Concrete Durability*

1 Introduction

Alkali silica reaction (ASR) has brought about severe durability challenges to affected concrete. This deterioration mechanism occurs as a result of the reaction between reactive silica in aggregates with alkalis from cement in concrete. The presence of an ample amount of water initiates the development of an ASR gel that can expand to cause cracks in affected concrete. Moisture has been confirmed to be a crux for the reaction (Lenzner, 1981; Tomosawa et al., 1989; Poyet et al., 2006; Deschenes et al., 2018; Olajide et al., 2022); it acts as a reactant and for the imbibition by the ASR gel. Due to such importance, the reduction in moisture has been fundamental for the prevention and mitigation of the reaction. Given the climatic changes in North America and European countries, concrete is subjected to alternate wetting and drying seasons. In the Winter and Spring, outdoor structures are exposed to wetting which is favorable for the development of ASR. The reaction could however be halted or reduced in the Summer due to increased drying. Despite the advantage of the drying regime in the maintenance of affected structures, the successive wetting and drying cycles could exacerbate concrete deterioration (Stark et al., 1993; Farny & Kerkhoff, 2007). Several studies exist on the influence of wetting and drying cycles on the kinetics of ASR and its induced expansion in affected concrete (Poyet et al., 2006). However, research is lagging on the assessment of internal damage resulting from the alternate wetting and drying conditions. The condition assessment of ASR affected concrete infrastructures has greatly evolved over the years; the coupling of tools for the appraisal of inner damage resulting from ASR induced expansion and associated reduction in mechanical properties has become more popular (Sanchez et al., 2017).

For the appraisal of ASR induced internal damage in concrete, the damage rating index (DRI) has been prominently used (Rivard & Ballivy, 2005; Sanchez et al., 2015; Cukierski, 2021). The analysis is a petrographic technique based on the semi-quantification of cracks in polished ASR affected specimens. Cracks are counted using a stereomicroscope of 15-16X magnification and these counts are multiplied by a weighting factor depending on their relevance. The output of such analyses is a DRI number obtained by summing the weighted counts and normalizing to $100cm^2$. The DRI number has been reported to increase as the ASR induced deterioration increases.

The wetting condition has been established to be favorable for the development of ASR, hence, the initiation and propagation of cracks from the aggregate particles into the cement paste. However, the effect of the alternate wetting and drying condition on crack properties in ASR affected concrete is unknown. This study exposed concrete specimens of different level of aggregate reactivity to constant moisture and wet - dry cycles. Then, the DRI was carried out on the specimens to assess the influence of the exposure conditions on microscopic properties.

2 Materials and Methods

2.1 Mix Proportion and Specimen Preparations

Forty-eight concrete cylinders with dimensions of 100 x 200 mm and mixture design strength of 45MPa was batched in the laboratory using one manufactured sand (non-reactive fine aggregate) and two reactive coarse aggregates (Spratt: highly reactive, Sudbury: moderately reactive). Table 1 presents the mixture proportions selected for this experiment as per ASTM C1293. A Portland cement containing 0.86% Na_2O_{eq} was used and the alkali content was boosted to 1.25% Na_2O_{eq} by cement mass to trigger the development of ASR.

Table 1. Concrete mixture proportion.

Materials	Spratt (kg/m^3)	Sudbury (kg/m^3)
Cement	420	420
Coarse	1000.45	984.41
Fine	822.98	799.52
Water	177.4	177.4
NaOH	2.12	2.12

Two different set of concrete specimens were manufactured: Spratt (SP) and Sudbury (SB) containing concrete specimens. All concrete specimens were demolded after 24 hours and moist cured for another two days; during this time the specimens were drilled on both sides and stainless-steel studs of 8-3/4 inch in dimensions were installed with the aid of a fast-setting cement slurry. After installing the studs and an additional 48 hours of moist curing, the initial measurements were taken, and the specimens were stored in the various exposure conditions discussed in section 2.2 to accelerate ASR development.

2.2 Exposure Conditions

Three different exposure condition scenarios were selected for this experiment: A) constant temperature and relative humidity of 38ºC and 100% RH (the standard exposure for ASTM C 1293). B) constant temperature and relative humidity of 21ºC and 100% RH. C) Wet (21ºC/100% RH) - dry (38ºC/82% RH) cycles.
The cyclic values (RH and temperature) were selected to give a close idealization of the variation of these conditions in field. Basically, high temperature in the Summer is accompanied with reduced relative humidity while a more humid condition and drop in temperature is experienced in other seasons.
The constant conditions were achieved by placing the concrete cylinders in a sealed bucket containing water at the bottom and stored at a temperature of 38ºC or 21ºC for one year. On the other hand, as shown in Figure 1, the wet – dry cycles are achieved by first conditioning the specimens to a wet environment (21ºC/100% RH) for a period of 28 days and then transferring them to a dry condition (38ºC/82% RH) for another 28 days. This cycle was repeated for 1 year. The 100% RH was achieved using clean water that is deposited at the bottom of the bucket while the 82% RH was controlled with the aid of saturated salts according to the ASTM E104. Sensors were placed inside the buckets to monitor the relative humidity and temperature over time. Both concrete mixtures (SP and SB) were each subjected to three different exposure scenarios. Each bucket contained 4 replicate samples.

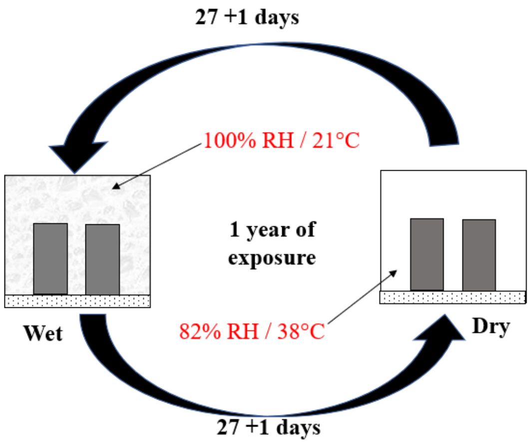

Figure 1. Wet-dry cycles.

2.3 ASR Expansion Measurements

All the specimens (SP and SB) in each exposure condition were monitored for length changes every 28 days for a period of 1 year. According to the ASTM C1293, all the specimens were kept at room temperature 18-24 hours before each length measurement. Each specimen is measured three times and average expansion value was recorded.

2.4 Damage Rating Index (DRI)

After 1 year of length measurements for all specimen in each exposure condition, one sample was selected from each family for the DRI analysis. Each specimen was cut axially into two halves and one side was polished with the aid of a hand polishing machine until a flat and well-polished surface was achieved using grits of range 50 - 3000. Thereafter, grids of 1cm x 1cm were drawn on the surface of the polished specimens and a microscope of 16x magnification was then used to carry out a petrographic assessment of the surface. The total number of each petrographic feature highlighted in Figure 2 is multiplied by their corresponding weighting factors. The total weighted count is then normalized to 100cm² to give the DRI number for each specimen.

Features	Weighting factors
CCA: Cracks in coarse aggregates	0.25
OCA: Open cracks in coarse aggregates	2
OCAG: Cracks with reactive products in aggregates	2
CAD: Coarse aggregate debonded	3
DAP: Disaggregated/corroded aggregate particle	2
CCP: Cracks in cement paste	3
CCPG: cracks with reation products in cement paste	3

Figure 2. Distress features and weighting factors (Villeneuve & Fournier, 2012)

3 Results and Discussions

3.1 ASR Kinetics

The average expansions as a function of time of the concrete cylinders incorporating Spratt and Sudbury reactive coarse aggregates at different exposure conditions are presented in Figure 3. According to Fig. 3A, the increase in temperature from 21ºC to 38ºC improved the kinetics of the reaction in Spratt specimens, leading to an ultimate expansion of ~0.11% and ~0.22% in 21ºC and 38ºC, respectively. A similar trend was observed in the Sudbury specimens (Fig. 3B). As shown in both Figures, the ultimate expansion is greater in Spratt specimens compared to their counterparts in Sudbury for all similar exposure conditions. Confirming the different reactivity levels of both aggregates.
In the wet – dry cycles, an ASR induced expansion (amount differs depending on the reactivity level of the aggregates; Spratt versus Sudbury) was recorded in the first wet cycle as a result of

the availability of sufficient moisture. The loss of capillary water due to drying in the first drying cycle results to the reduction in the available moisture for imbibition by the ASR gel, leading to the record of a negative deformation i.e. relative shrinkage. A similar level of shrinkage was attained in both aggregates at 56 days. However, the Spratt specimens recovered to attain a net expansion of ~0.0080% in the second wet cycle (Day 84) while the Sudbury specimens remained in a net shrinkage condition at the similar age. One will notice that subsequent wet and dry cycles result in ASR induced expansion and shrinkage respectively. Even so, Sudbury does not attain a net ASR induced expansion until after 196 days. Before this age, expansion due to ASR was not sufficient to exceed the deformation resulting from drying shrinkage.

At 365 days for Spratt, expansions are 0.12% for cyclic condition and 0.11% for constant RH at 21ºC. The deformation in the cyclic condition progressed beyond that at constant 21ºC conditions. Hence, the introduction of a drying regime slows down the rate of the reaction, but ultimate expansion is higher. Nonetheless, this could be dependent on the reactivity level of the aggregate, as shown in Figure 3B, an opposite trend was observed for the ultimate expansion in Sudbury specimens, nevertheless, the rate of ASR induced expansion was reduced in the cyclic conditions. It is however worth noting that the ultimate expansion in the cyclic and constant RH at 21ºC conditions are quite close.

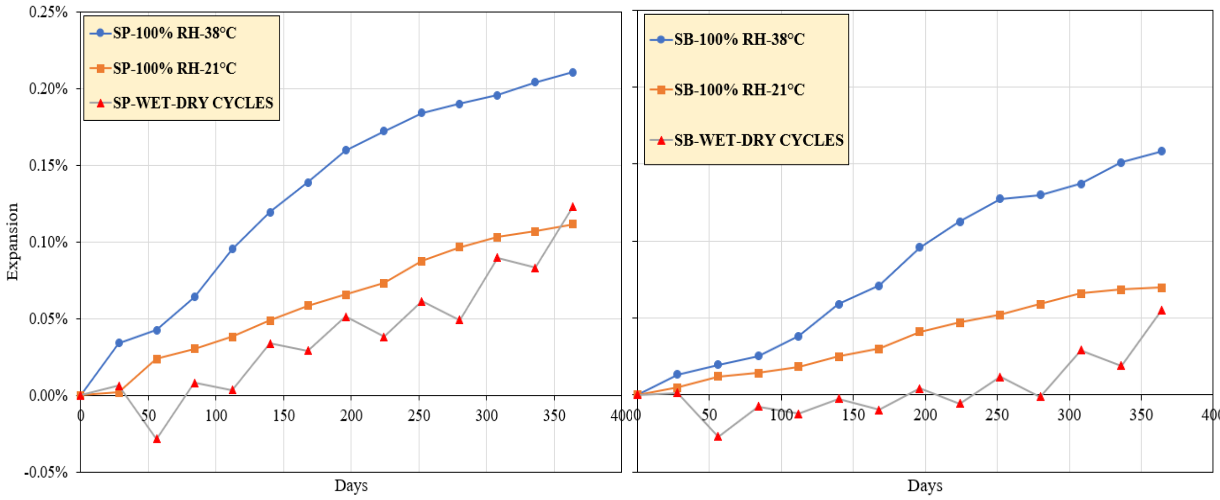

Figure 3. Expansion as a function of time A) Spratt, B) Sudbury

3.2 Damage Rating Index

Fig. 4 shows the DRI chart obtained for all the exposure conditions and aggregates evaluated in this study with corresponding 1 year ASR induced expansion measurements. The DRI number for Spratt specimens ranges from 403 – 695, while Sudbury specimens are in the range of 186 – 434, both depending on the exposure conditions. Spratt in constant RH at 38ºC (~0.21% expansion) and Sudbury in constant RH at 38ºC (~0.16% expansion) has a DRI number of 695 and 434, respectively. Their counterparts at 21ºC with 0.11% expansion (Spratt) and ~0.07% expansion (Sudbury) have DRI numbers of 403 and 195 respectively. This confirms the efficiency of the DRI to appraise damage due to ASR (higher level of ASR induced expansion results in higher DRI number) irrespective of the aggregate type and exposure conditions. Evaluating the DRI chart for the constant RH in both aggregates and temperatures, one will notice that the open cracks in aggregates with and without reaction products (i.e. OCAG and OCA) and the cracks in the cement paste with and without reaction products (i.e. CCPG and CCP) increases as expansion increases. Cracks in the aggregates (CCA, OCA, OCAG) and in the cement paste without reaction products (CCP) are counted in all exposure conditions and aggregates. However, cracks in the cement paste with reaction products (CCPG) are only present at expansion levels greater than 0.1%.

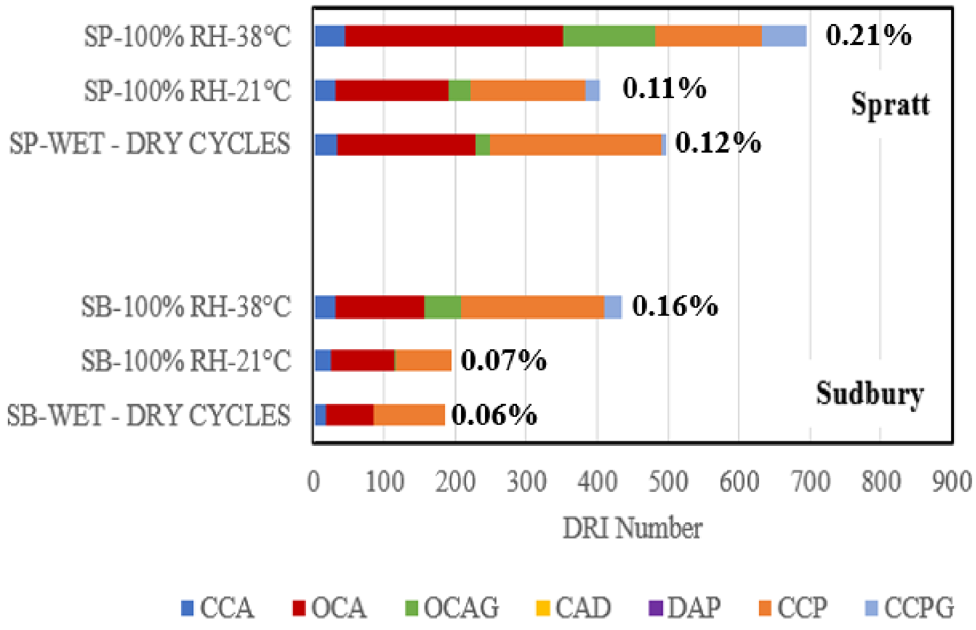

Figure 4. DRI outcomes as a function of reactive aggregates and exposure conditions with 1 year ASR induced expansion results.

Comparing the constant RH at 21ºC and wet - dry cycle for Sudbury aggregates, one will realize they have almost similar DRI number, but their ASR induced petrographic features differ. The constant RH has an OCA of 47% of the total microscopic cracks compared to 36% in the wet – dry cycles confirming a higher ASR induced deterioration at the constant RH condition which correlates with the expansion results. Furthermore, a higher number of cracks in the cement paste (i.e CCP) was recorded in the wet-dry cycles (54%) compared to the constant RH condition (40%). The high CCP is as a result of the drying shrinkage during the dry cycles.
As previously stated, the reactivity of the aggregates affects the kinetics of the ASR, so is the ASR induced deterioration. Considering the DRI results obtained for Spratt at constant RH (21ºC) and wet – dry cycles, higher DRI number of 493 was obtained in the wet-dry cycles compared to the 403 obtained at the constant RH condition which mirrored the observation in the ASR induced expansion results in Fig. 3A. High CCP was recorded in the wet-dry cycles due to shrinkage. Furthermore, more cracks are counted in the aggregates (OCA + OCAG) than those at constant RH (2º1C) which confirms an enhanced ASR development in the cyclic condition. While still comparing the Spratt constant RH at 21ºC and wet – dry cycles, another

point to note is that despite both having close expansion (~0.11% and ~0.12% respectively), the induced deterioration (petrographic features and DRI number) slightly differs. The difference in the induced deterioration can be attributed to the drying cycles during which the ASR gel has less moisture and full swelling potential could not be attained. But the increase in temperature improves the mobility and concentration of ions leading to improved kinetics and subsequently more damage in the following wet cycles. Hence, inner damage can be exacerbated due to the cyclic conditions of wetting and drying. However, based on the expansion results, ASR induced deterioration might be less pronounced in the early ages.

4 Conclusions

- The results of the ASR induced expansion clearly shows that the kinetics of the reaction varies with the reactivity level of the aggregates at constant moisture. Higher kinetics, expansion and induced internal distress were attained in Spratt specimens compared to Sudbury.
- Specimens exposed to the wet-dry cycles experienced ASR induced expansion during the wet cycles regardless of the aggregate type. Each drying cycle leads to a reduced available moisture resulting in drying shrinkage in the samples. The rate of the shrinkage seems similar in both aggregate types. However, Spratt expands more rapidly upon re-exposure. Therefore, the rate of ASR induced expansion in the wet cycles could be dependent on the reactivity level of the aggregates.
- Comparing the results from the constant and wet – dry cycles conditions, one will notice that the alternating cycles can reduce the rate of the reaction especially at the early ages. Evidently from the expansion results, for instance, the ASR kinetics of Sudbury and Spratt specimens in the wet – dry cycles are much lower than their counterparts at constant RH (21ºC). However, the coupling of ASR with drying shrinkage due to the dry regimes can accelerate the reaction at late ages and the cyclic conditions can attain a higher ultimate expansion. This was only confirmed in the Spratt specimens in Fig. 3A, however, a similar conclusion looks likely in the Sudbury specimens given the rate of expansion in the last wet cycle.
- The alternate wet – dry cycles can influence the microstructural properties of affected concrete. Sudbury specimens exposed to these conditions exhibit higher cracks in the cement paste. However, the Spratt specimens in similar condition exhibit higher cracks both in the aggregates and cement pastes. Hence, induced ASR deterioration is higher than in constant RH at 21ºC. As a result, the DRI can provide a reliable assessment of the role of constant and variable mositure and temperature in ASR induced internal distress.

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